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## Dependence of Power and Efficiency of AlGaIn/GaN HEMT's on the Load Resistance for Class B Bias

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The material properties of GaN and the AlGaIn/GaN heterostructure such as high breakdown field and high sheet charge density, allow AlGaIn/GaN HEMTs to be operated at significantly higher drain bias voltages as compared to other III-V compound semiconductor FETs [1]. As expected, larger RF voltage and current swings result in higher normalized output power at microwave frequencies. AlGaIn/GaN HEMT's are capable of generating output power density in excess of 10W/mm [2], [3] in X-band, which is at least an order of magnitude larger than what is obtainable with GaAs FETs. In this paper, we will discuss the effect of the load impedance on measured output power ( $P_{out}$ ) and efficiency ( $\eta$ ) at various drain bias conditions in Class B mode. Dynamic loadlines extracted at the device's output are used for analysis of the trade-off between voltage and current swings at different load resistances and its effect on output power and efficiency.

### I. Theoretical Background

Load impedance is related to the reflection coefficient at the device's output plane as

$$Z_{load} = R_{series} + jX_{series} = Z_0 \frac{1 + \Gamma_{load}}{1 - \Gamma_{load}} \quad (1)$$

Load admittance can be represented as

$$Y_{load} = \frac{1}{R_{load}} - j \frac{1}{X_{load}} = \frac{R_{series}}{R_{series}^2 + X_{series}^2} - j \frac{X_{series}}{R_{series}^2 + X_{series}^2} \quad (2)$$

For the purpose of direct correlation between the load resistance and the complex reflection coefficient, it is more illustrative to represent device loading conditions in terms of parallel combination of load conductance and load susceptance. The inverse of load conductance (real part of load admittance) in equation (2) is the actual load resistance connected in parallel across the drain-source junction of a FET.

The same value of the load resistance  $R_{load}$  appears as a negative slope of a symmetry axis of measured dynamic loadlines (see Figures 4 and 5). On the other hand, loadline looping is caused by series reactance  $X_{series}$ , which makes the output current lag behind the output voltage waveform (in a case of inductive reactance). When series reactance becomes zero, voltage and current waveforms are exactly in antiphase, the loadline becomes purely resistive and collapses onto a line with the slope equal to the negative of the load resistance.

To extract maximum possible microwave output power from an active semiconductor device, a specific load impedance has to be presented at the output device plane. Usually, the load impedance corresponding to the maximum output power is not the same as the ones corresponding to the maximum transducer gain ( $G_t$ ), drain efficiency ( $\eta$ ).

Optimum load impedances for optimum power and efficiency will be analyzed for Class B bias, when the device is biased at pinch-off. In the absence of RF current slump, this bias mode is preferable for high drain voltage operation of AlGaIn/GaN HEMT's due to minimization of the adverse thermal effects. Also, we will make the following assumptions: 1) breakdown voltage is infinity; 2) second and higher harmonics are properly terminated such that microwave voltage waveform is sinusoidal and microwave current waveform is a half-wave rectifier. Under these assumptions the power of a Class B signal is equal to

$$P_{out} = \frac{V_{max} - V_{min}}{2\sqrt{2}} \frac{I_{peak}}{2\sqrt{2}} = \frac{(V_{ds(bias)} - V_{min}) I_{peak}}{4}, \quad (3)$$

where  $V_{min}$  and  $V_{max}$  are the two extrema of the voltage waveform and  $I_{peak}$  is the peak of the current waveform with zero being the minimum.

Drain efficiency is defined as the ratio of output power to dissipated DC power

$$\eta = \frac{P_{out}}{V_{ds(bias)} I_{ds(bias)}} \quad (4)$$

For Class B bias, DC (average) value of the drain current can be shown to be equal to

$$I_{ds(bias)} = \frac{I_{peak}}{\pi} \quad (5)$$

Power and drain efficiency will be analyzed for the three types of loadlines shown in Figure 1.

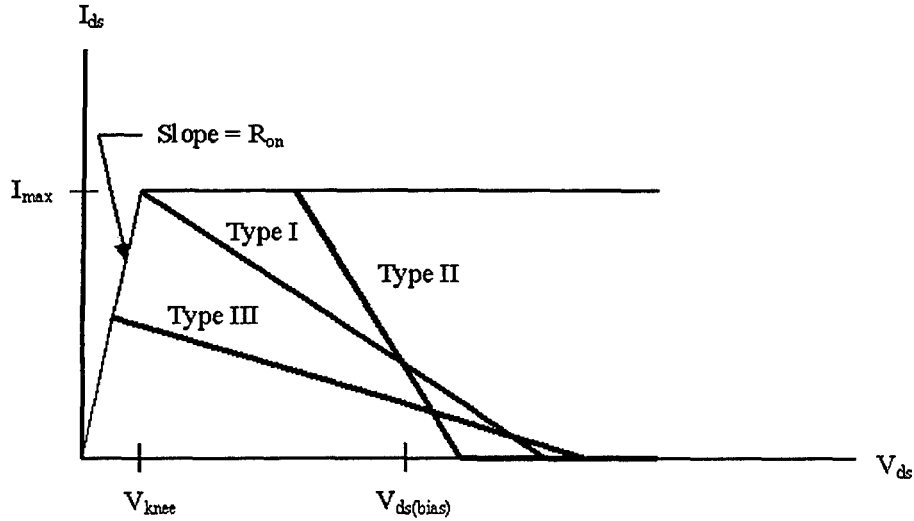


Figure 1. Three Types of Analyzed Loadlines

If we neglect the effect of reflection from the load, optimal load impedance resulting in maximum  $P_{out}$  (loadline of Type I in Figure 1), i.e. in simultaneous maximization of microwave voltage and current swings, is purely resistive and equal to

$$Z_{load(P_{out})} = \frac{\pi}{\pi - 1} \frac{V_{ds(bias)} - V_{knee}}{I_{max}} + j0, \quad (6a)$$

where  $I_{max}$  is the open-channel current and  $V_{knee}$  is the minimum drain-source voltage at which  $I_{max}$  is attainable.

The maximum output power and drain efficiency corresponding to the load impedance  $Z_{load(P_{out})}$  are equal to

$$P_{out\ max} = \frac{(V_{ds(bias)} - V_{knee}) I_{max}}{4} \quad (6b)$$

$$\eta = \frac{\pi}{4} \frac{V_{ds(bias)} - V_{knee}}{V_{ds(bias)}} \quad (6c)$$

For an ideal case of  $V_{knee}$  being 0V, drain efficiency for Class B is equal to  $\pi/4=78.5\%$ .

Load resistance smaller than  $\text{Re}(Z_{load(P_{out})})$ , corresponding to the loadline of Type II in Figure 1, results in the maximum RF current swing and reduced RF voltage swing.  $I_{peak}$  is equal to the open-channel current  $I_{max}$ , the minimum RF voltage is larger than the knee voltage and is limited to

$$V_{min} = V_{ds(bias)} - \frac{\pi - 1}{\pi} I_{max} R_{load} > V_{knee} \quad (7a)$$

The resulting output power and corresponding drain efficiency are proportional to load resistance. Output power does not depend on drain bias voltage, while drain efficiency is inversely proportional to drain bias voltage

$$P_{out} = \frac{\pi - 1}{\pi} \frac{I_{max}^2 R_{load}}{4} < P_{out max} \quad (7b)$$

$$\eta = \frac{\pi - 1}{4} \frac{I_{max} R_{load}}{V_{ds(bias)}} < 78.5\% \quad (7c)$$

Load resistance larger than  $Re(Z_{load(Pout)})$ , corresponding to the loadline of Type III, results in reduced RF current swing but increased RF voltage swing. Both peak RF current and minimum RF voltage are functions of load resistance, on-resistance  $R_{on}$  and drain bias voltage:

$$I_{peak} = \frac{\pi}{(\pi - 1)R_{load} + \pi R_{on}} V_{ds(bias)} < I_{max} \quad (8a)$$

$$V_{min} = \frac{\pi R_{on}}{(\pi - 1)R_{load} + \pi R_{on}} V_{ds(bias)} < V_{knee} \quad (8b)$$

and the corresponding output power and drain efficiency are

$$P_{out} = \frac{V_{ds(bias)}^2}{4} \frac{\pi(\pi - 1)R_{load}}{[(\pi - 1)R_{load} + \pi R_{on}]^2} < P_{out max} \quad (8c)$$

$$\eta = \frac{\pi}{4} \frac{(\pi - 1)R_{load}}{(\pi - 1)R_{load} + \pi R_{on}} \rightarrow 78.5\% |_{R_{load} \gg R_{on}} \quad (8d)$$

In this case, an increase in load resistance leads to an increase in drain efficiency up to 78.5% for  $R_{load} \gg R_{on}$ , and causes a decrease in the output power. Formula (8d) indicates that as long as the load resistance is larger than the optimum power load resistance defined in formula (6a), drain efficiency should be ideally independent of drain bias voltage. This observation is confirmed by experimental results presented below. Also, similar conclusions were reached by Y.-F. Wu [3] for class A bias-dependent operation of AlGaIn/GaN HEMT's.

Theoretical dependence of output power and drain efficiency on load resistance, derived assuming a finite on-resistance and using formulas (6b-c), (7b-c), (8c-d) are plotted in Figures 2 and 3. The optimum power load resistance results in the maximum efficiency only for zero on-resistance case. For a real device with some finite on-resistance, optimum efficiency load resistance will always be larger than the optimum power load resistance.

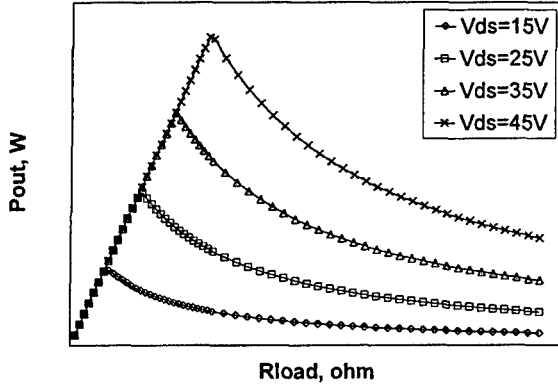


Figure 2. Theoretical Dependence of Output Power on Load Resistance

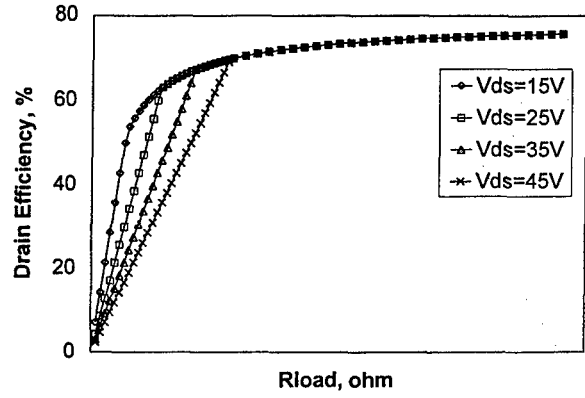


Figure 3. Theoretical Dependence of Drain Efficiency on Load Resistance

The load impedance, corresponding to the maximum small-signal transducer gain, is equal to the complex conjugate of the device output impedance in order to minimize reflection from the load

$$Z_{load(GI)} = Z_{out}^* \quad (9)$$

For optimum large-signal performance, some load reflection is inevitable due to the fact that optimum power and efficiency load resistances in most cases are going to be smaller than the device's output resistance. To compensate for the drain-source and drain pad capacitances, load impedance should contain some inductive reactance. This load reactance introduces a delay between microwave output current and output voltage waveforms. On the extreme, if the load reactance becomes infinitely larger than the load resistance, output current waveform lags the voltage waveform by 90°, and the active power at the fundamental frequency goes to zero.

In order to include the effect of reflection from the load, formula (3) for maximum output power has to be modified as follows

$$P_{out} = \frac{(V_{ds(bias)} - V_{min})I_{peak}}{4} \frac{1 - |\Gamma_{load}|^2}{|1 - \Gamma_{load}\Gamma_{out}|^2} \quad (10)$$

## II. Continuous Wave Power Measurements with 2<sup>nd</sup> Harmonic Termination

Power performance of AlGaIn/GaN HEMTs on SiC has been characterized using a harmonic load-pull system, in which fundamental source and load reflection coefficients can be varied from 0 to 0.8 in magnitude and from 0 to 180° in phase. 2<sup>nd</sup> harmonic load reflection coefficient has a range from 0 to 0.6 in magnitude and 0 to 180° in phase.

Continuous wave (CW) power measurements were made on a 0.25μm x 1.5mm device at 10 GHz. The gate bias was set very near pinch-off for class B operation. The source impedance was set to be the complex conjugate of the device input impedance to maximize power transfer between the signal source and the device. Then, two

fundamental load reflection coefficients of interest were determined and set. A second harmonic load pull was used to determine optimum 2nd harmonic load impedance. This allows one to approximate the microwave voltage waveform as an ideal sinusoid and microwave current waveform as half-wave rectifier.

Input power sweeps were taken at drain voltages from 15V to 40V with 5V steps at two load reflection coefficients. Reactive parts of load admittance (impedance) are attempted to be kept equal within the accuracy of the load-pull setup, and real parts differ to explore the effect of load resistance on bias-dependent large-signal device performance:

1)  $\Gamma_{load1}=0.703\angle 132^\circ$ , which corresponds to  $R_{load1}=53.4\text{ohm}$  and  $X_{load1}=26\text{ohm}$  as calculated based on formulas (1) and (2);

2)  $\Gamma_{load2}=0.695\angle 124^\circ$ , which corresponds to  $R_{load2}=79.8\text{ohm}$  and  $X_{load2}=34.4\text{ohm}$ .

1dB and 3dB compression output powers as functions of the drain bias voltage for both load reflection coefficients are shown in Figure 4. Drain efficiencies are shown in Figure 5.

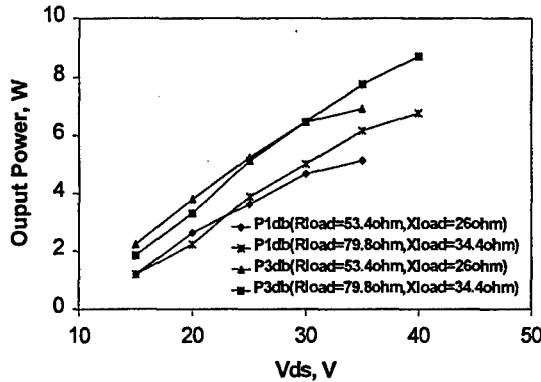


Figure 4. CW Linear and Maximum Output Powers Measured at 10GHz and Various Drain Bias Voltages for the two load impedances

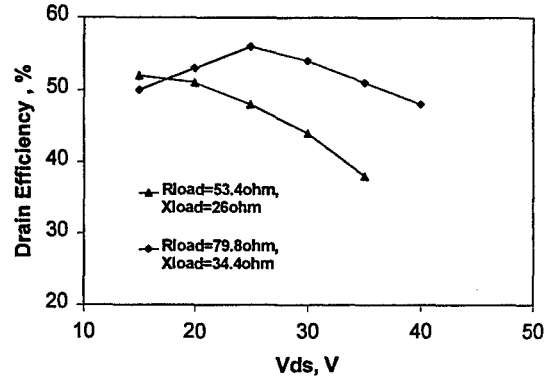


Figure 5. CW Drain Efficiency Measured at 10GHz and Various Drain Bias Voltages for the two load impedances

Loading the device with the load reflection coefficient  $\Gamma_{load1}$  results in slightly higher power and efficiency at low drain biases. However, at bias voltages above 20V, the load resistance  $R_{load1}=53.4\text{ohm}$  apparently becomes smaller than the optimum power load resistance as defined in formula (6a). As a result, efficiency starts to decrease with increase in the bias voltage as predicted by formula (7c). The continuous increase in the output power above 20V, contradicts formula (7b), according to which for a Type II loadline,  $P_{out}$  should be independent of the drain bias voltage. We attribute this phenomena to increase in  $I_{max}$  due to some finite output conductance and the floating-body effect, found by Nuttinck et al [4] in AlGaIn/GaN HEMT's on SiC substrates.

On the other hand, the load resistance  $R_{load2}=79.8\text{ohm}$  remains larger than the optimum power load resistance, meaning it stays the Type III loadline, up to drain bias voltage of 40V. Thus, drain efficiency is almost independent of the bias voltage as predicted by formula (8d). Also,  $R_{load2}$  yields more linear device response at large drain bias voltages as evidenced by higher 1dB compression power data in Figure 4.

### III. Pulsed Power Measurements with Dynamic Loadline Extraction

To visualize the effect of load resistance on RF output voltage and current waveforms, pulsed power measurements were performed at 8 GHz on Maury™ load pull system with HP Microwave Transition Analyzer (MTA) being used in place of input, reflected and output power meters. MTA allows to accurately measure power waveforms at its own calibration planes. The RF voltage and current waveforms at the device planes are then extracted by using the known load tuner's scattering parameter matrices at fundamental, second and third harmonics [5]. The RF loadlines, expressed as functions  $I_{out} = f(V_{out})$  are then plotted.

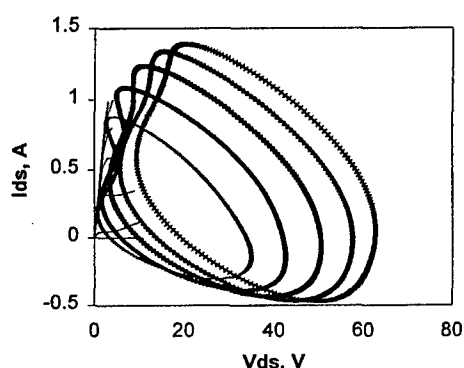
To minimize thermal effects and alleviate reduced device performance due to rise in the channel temperature, the pulse width was set to 500 ns with 1% duty cycle.

Loadlines for two load impedances:

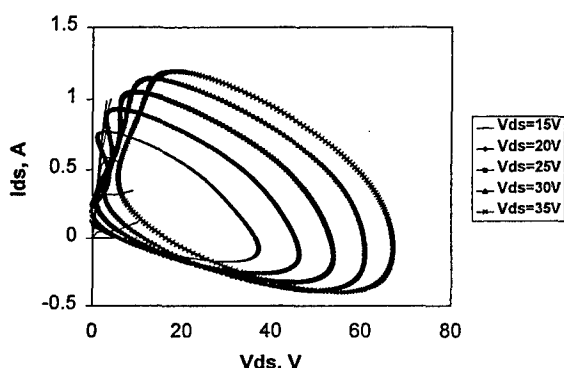
1)  $R_{load}=53.1\text{ohm}$ ,  $X_{load}=35.8\text{ohm}$ ;

2)  $R_{load}=78.2\text{ohm}$ ,  $X_{load}=48.5\text{ohm}$

for drain voltages from 15 to 35V are plotted in Figures 6 and 7.



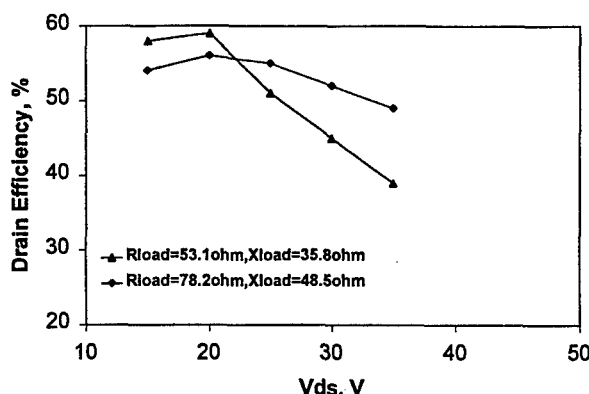
**Figure 6.** Pulsed Dynamic Loadlines Measured at 8GHz and Various Drain Bias Voltages for  $R_{load}=53.1\text{ohm}$   $X_{load}=35.8\text{ohm}$



**Figure 7.** Pulsed Dynamic Loadlines Measured at 8GHz and Various Drain Bias Voltages for  $R_{load}=78.2\text{ohm}$   $X_{load}=48.5\text{ohm}$

Similarly to the 10 GHz CW results, drain efficiency, as shown in Figure 8, for the larger load resistance varies insignificantly with drain bias voltage, and the minimum RF voltage is only limited by the DC knee voltage, which helps to maximize RF voltage swing. On the other hand, smaller load resistance becomes less than the optimum power load resistance at approximately 25V drain bias voltage. At this point, minimum RF voltage becomes limited by the open-channel current and starts to increase with the bias voltage, which causes the drain efficiency to drop.





**Figure 8.** Drain Efficiency Measured Under Pulsed Conditions at 8GHz and Various Drain Bias Voltages for the two load impedances

### III. Conclusions

We investigated the effects of the load resistance on large-signal performance of discrete AlGaIn/GaN HEMT's. Observed functional dependencies of output power and drain efficiency at various load resistances and drain bias voltages are explained analytically in terms of device's DC I-V metrics: the open-channel current, knee voltage and on-resistance.

Measured dynamic loadlines for the two load resistances of interest at different bias voltages allowed visualization of the limiting mechanisms and trade-offs between RF voltage and current swings and their effect on output power and efficiency.

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